How To Measure Absolute Luminosity

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References :

[1] AN184, S. Belikov *et al.*

[2] "Luminosity Measurements and Calculations", K. Potter, CERN Particle Accelerator School Lectures, 1985.

[3] "Luminosity Optimisation for Storage Rings with Low-β Sections and Small Crossing Angles", E. Keil, NIM **113**, 333 (1973).

Overview

- What do we mean by Absolute Luminosity? (5%)
- Why do we need to measure it? (5%)
- How do we measure it? (90%)
  - What exactly is a Vernier Scan?
  - Description of the hardware involved (DCCTs, WCMs, BPMs)
  - Sample Data

What do we mean by Absolute Luminosity?

- Luminosity is proportionality between event rate $\dot{N}$ of process with cross section σ :

$$\dot{N} = \mathcal{L}\sigma$$

- Typically given in cm^{-2}s^{-1}
- N_y target particles uniformly distributed over area A of zero thickness
- Probability of single beam particle colliding head-on is $N_y \times \sigma / A$
- If N_b beam particles, total number of collisions $N = N_b \times N_y \times \sigma / A$

$\Rightarrow$ For k_b bunch pairs intersecting at frequency f_{rev}, total event rate :

$$\dot{N} = \left[k_b \times f_{rev} \times \frac{N_b \times N_y}{A} \right] \times \sigma$$

$$\Rightarrow \mathcal{L} = k_b \times f_{rev} \times \frac{N_b \times N_y}{A}$$

For zero-length bunches with non-uniform charge distributions :

$$d\mathcal{L} = k_b \times f_{rev} \times \frac{\rho_b(x,y)dxdy \;\times\; \rho_y(x,y)dxdy}{dxdy}$$

$$\Rightarrow \mathcal{L} = k_b \times f_{rev} \times \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \rho_b(x,y)\rho_y(x,y)dxdy$$

What do we mean by Absolute Luminosity?

For Gaussian beams with N_b and N_y particles colliding head-on :

$$\mathcal{L} = k_b \times f_{rev} \times \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho_b(x,y)\rho_y(x,y)dxdy$$
$$\Rightarrow k_b \times f_{rev} \times \frac{N_b \times N_y}{2\pi\sqrt{(\sigma_{bx}^2 + \sigma_{yx}^2)(\sigma_{by}^2 + \sigma_{yy}^2)}}$$

- Luminosity probably 2nd most important machine parameter, after beam energy

Why do we need to measure Absolute Luminosity?

Many PHENIX papers discuss the measurement of an invariant cross-section :

$$E\frac{d^3\sigma}{dp^3} \approx \frac{N}{\mathcal{L}} \frac{1}{2\pi p_T} \frac{1}{\Delta p_T \Delta y} \frac{1}{\eta_{\text{trig}}} \frac{1}{\eta_{\text{recon}}}$$

- We usually need $\mathcal{L}$ to extract cross-sections
- Knowing σ and $\mathcal{L}$ useful for calibrating detector efficiencies, geometric acceptances, ...
- Required to calibrate detectors (BBC, ZDC) which can then be used as luminosity monitors $\dot{N}_{\text{monitor}} = \mathcal{L}\,\sigma_{\text{monitor}} \Rightarrow \mathcal{L} = \dot{N}_{\text{monitor}}/\sigma_{\text{monitor}}$
- Important feedback for CAD for tuning beam, evaluating performance

How do we measure Absolute Luminosity?

$$\mathcal{L} \approx k_b \times f_{rev} \times \sum_{i=1}^{k_b} \frac{N_b^i \times N_y^i}{2\pi\sqrt{(\sigma_{bx}^{i\,2} + \sigma_{yx}^{i\,2})(\sigma_{by}^{i\,2} + \sigma_{yy}^{i\,2})}}$$

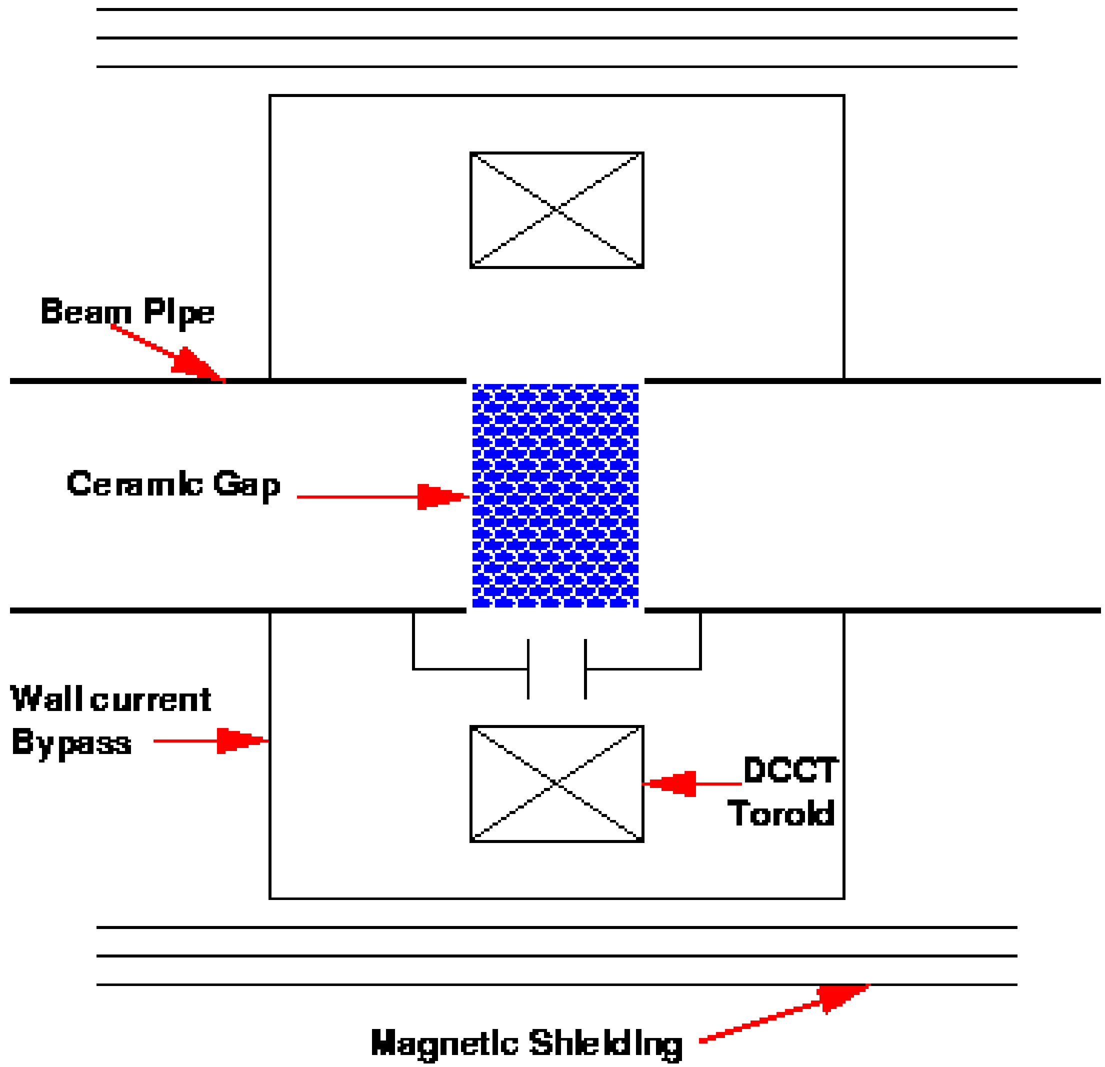
- To measure the number of ions N_b and N_y in each colliding bunch pair we use :
  - DCCT = D.C. current transformer
  - WCM = Wall Current Monitor
  - $k_b \approx 60, \ f_{rev} \approx 78.2$ kHz
- Beam overlap integral (effective width and height) determined with vernier scan
  - Requires knowledge of event rates (BBC, ZDC) versus beam displacement
  - Beam displacement measured with Beam Position Monitors (BPMs)

Beam Ion measurement with the DCCTs

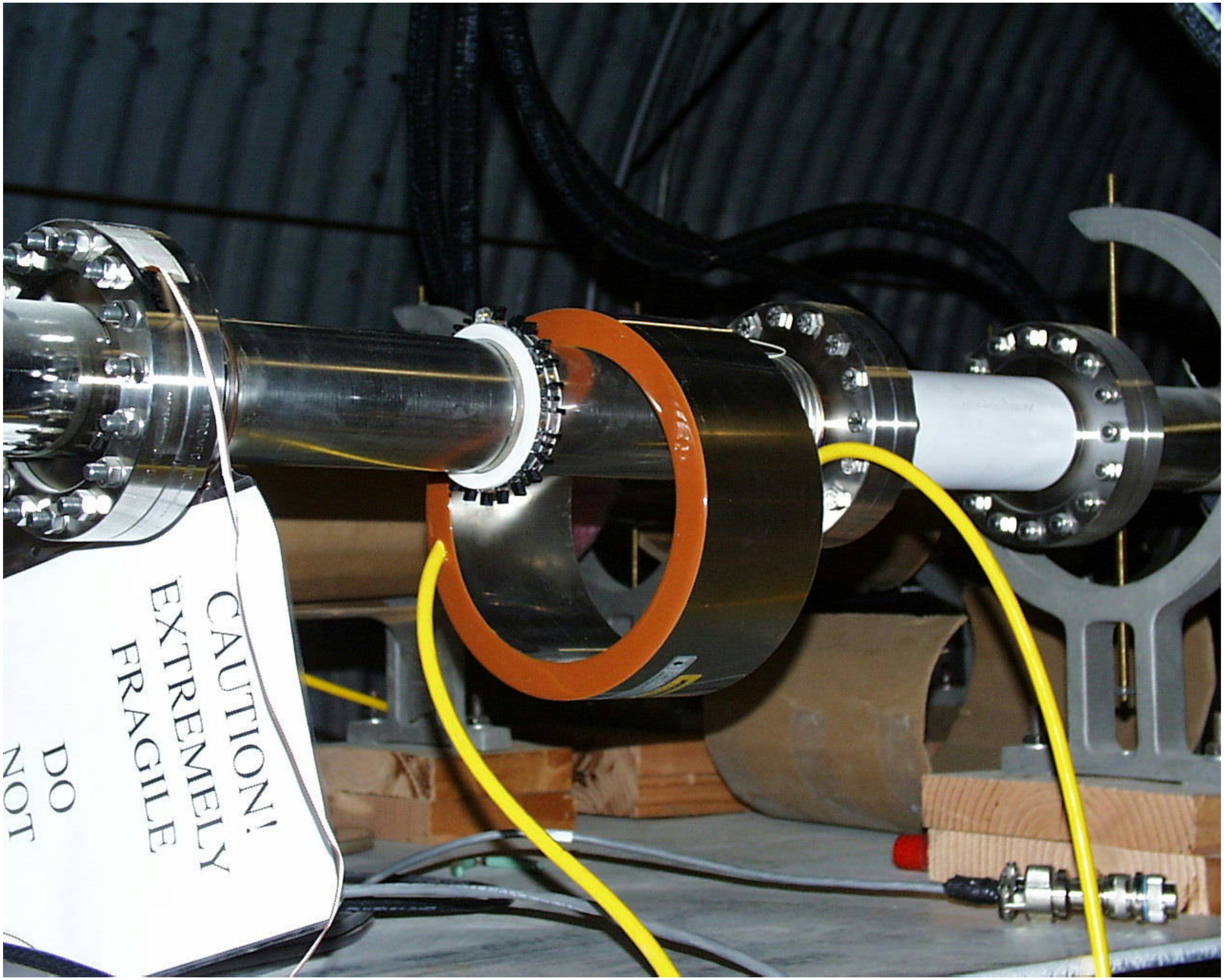
- D.C. current transformer designed in 1969 by Klaus Unser for the ISR
- One DCCT for blue and one for yellow at 2 o'clock
- Consists of high permeability toroid around beam with three windings
- One set of coils drives toroid into positive then negative saturation
- Sense windings detect flux changes, produce symmetric positive and negative voltage
- If beam current $\neq$ 0, acts like shift in H, coil driven to different parts of $B - H$ curve - positive and negative swings no longer balanced
- Second harmonic of sense signal is fedback to third winding to cancel flux from beam
- Voltage across precision resistor in series with third winding is proportional to beam current
- Measures average current over integration period of $\approx$ 1 second (hence DC) with $\approx$ 0.2% absolute accuracy, 50 μA rms resolution, $\pm$ 0.01$\%$ linearity error
- Long integration period means insensitive to bunched/unbunched beam, can't measure charge in individual bunches
- Calibrated with precision current source at startup
- Demagnetized after each beam dump to minimize "memory" effects

Beam Ion measurement with the DCCTs

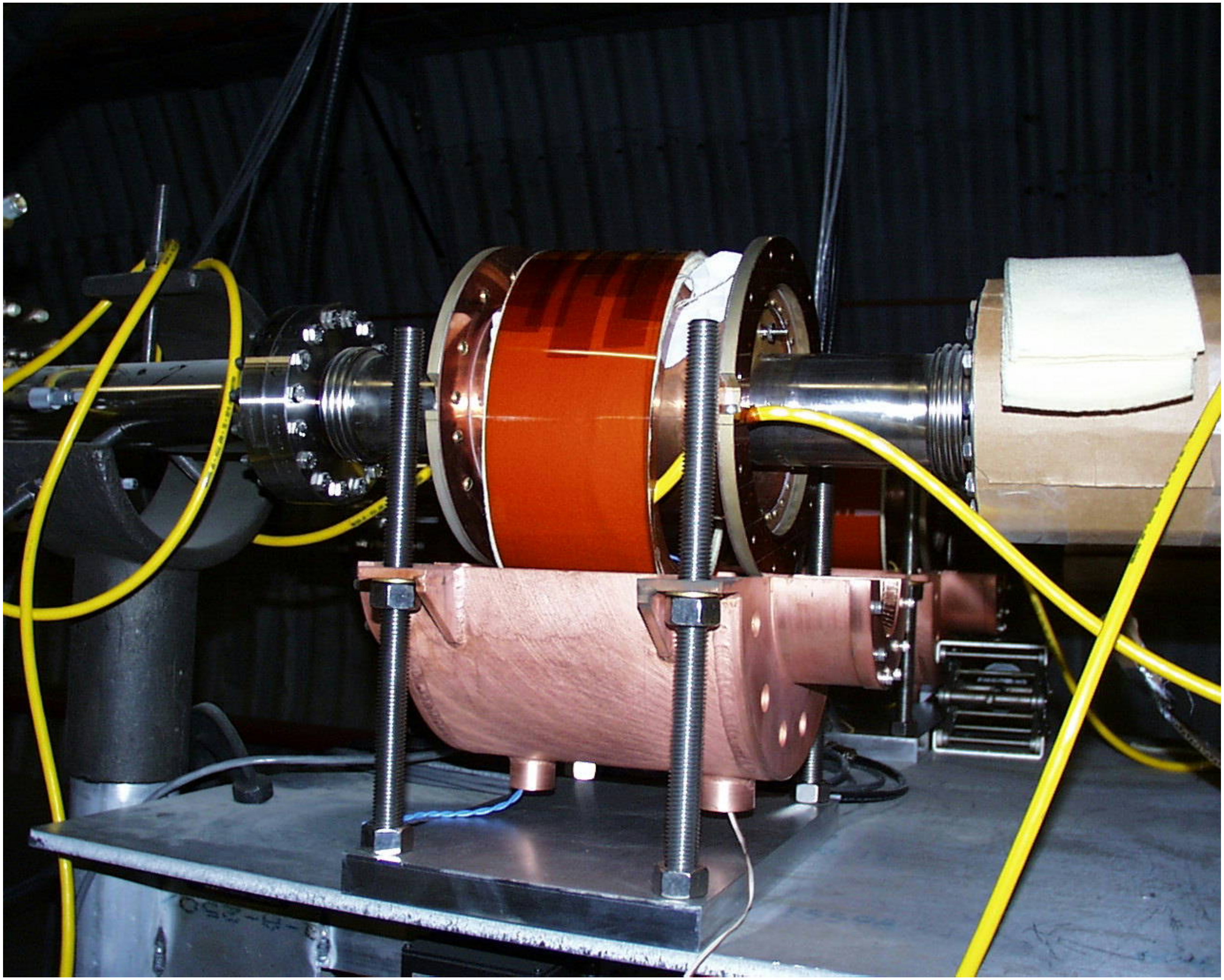
- Insulating ceramic break in beam-pipe shunts wall currents around toroid
- Magnetic shielding excludes external magnetic fields
- Only beam current threads core



Beam Ion measurement with the DCCTs

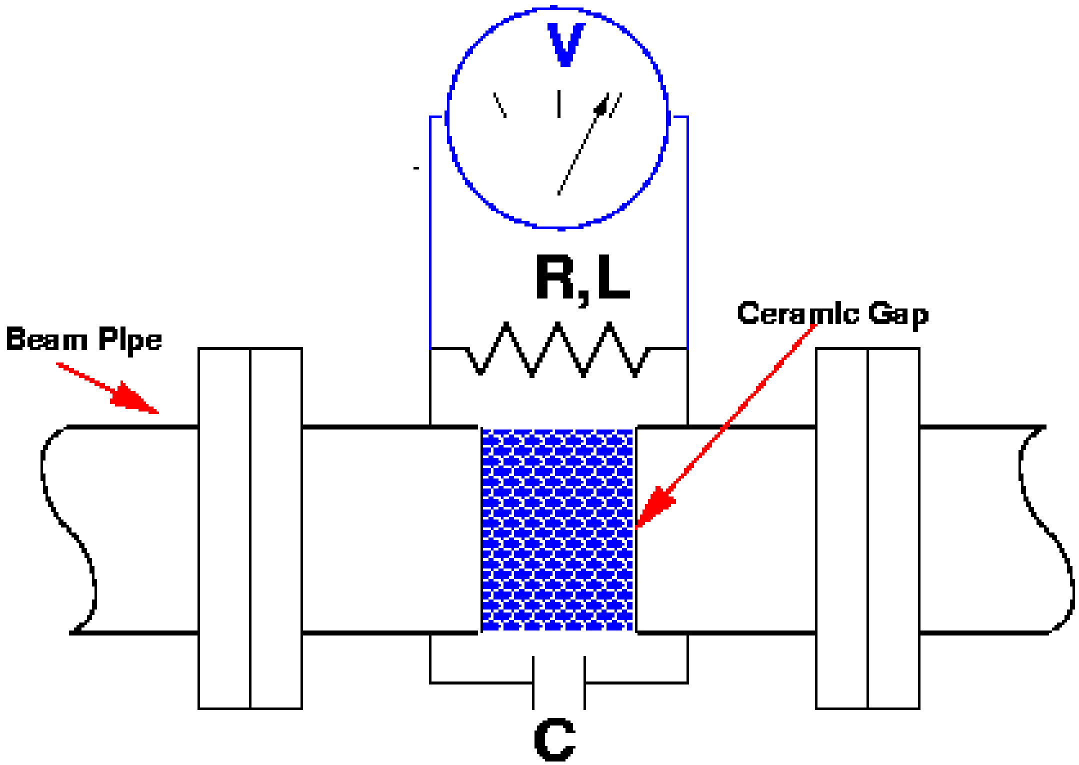


Beam Ion measurement with the DCCTs

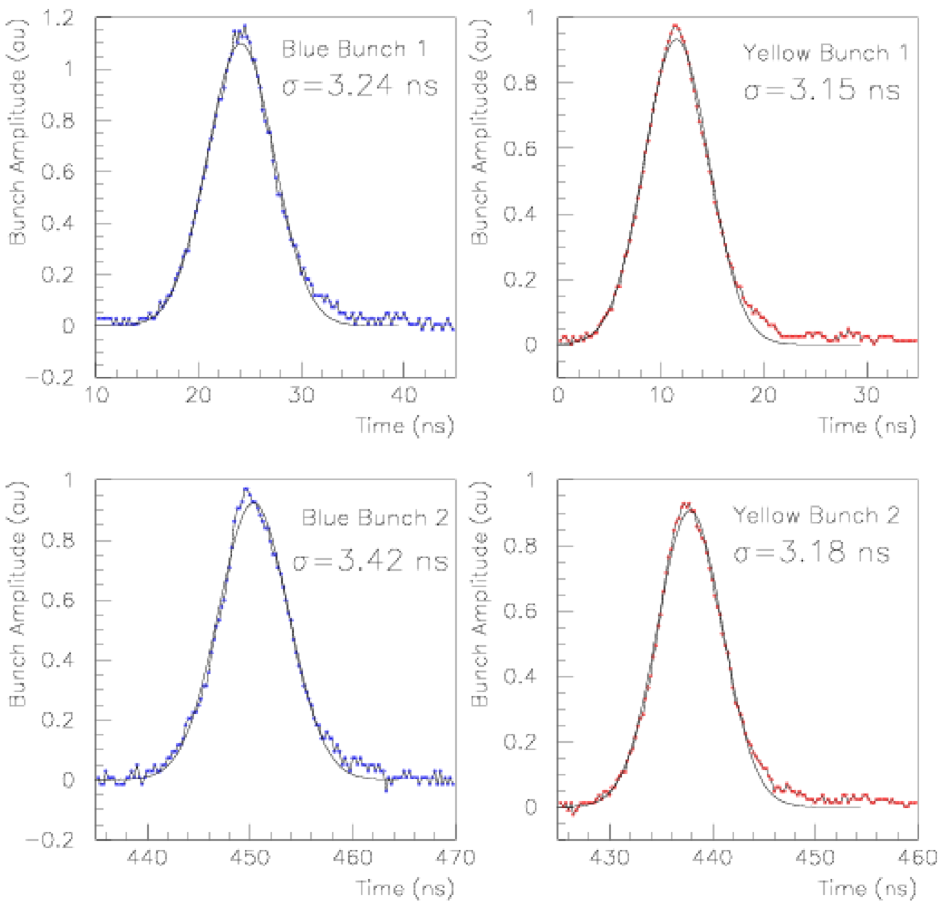


Beam Ion measurement with the WCMs

- Insulating ceramic break in beam-pipe forces image wall currents through resistors
- $\omega_{\text{low}} \approx R/L$
- $\omega_{\text{high}} \approx 1/RC$, few GHz
- Sensitive only to bunched beam
- Less accurate then DCCT
- Calibrate WCM with DCCT each fill after ramp when no un-bunched beam
- Can measure bunch longitudinal profiles

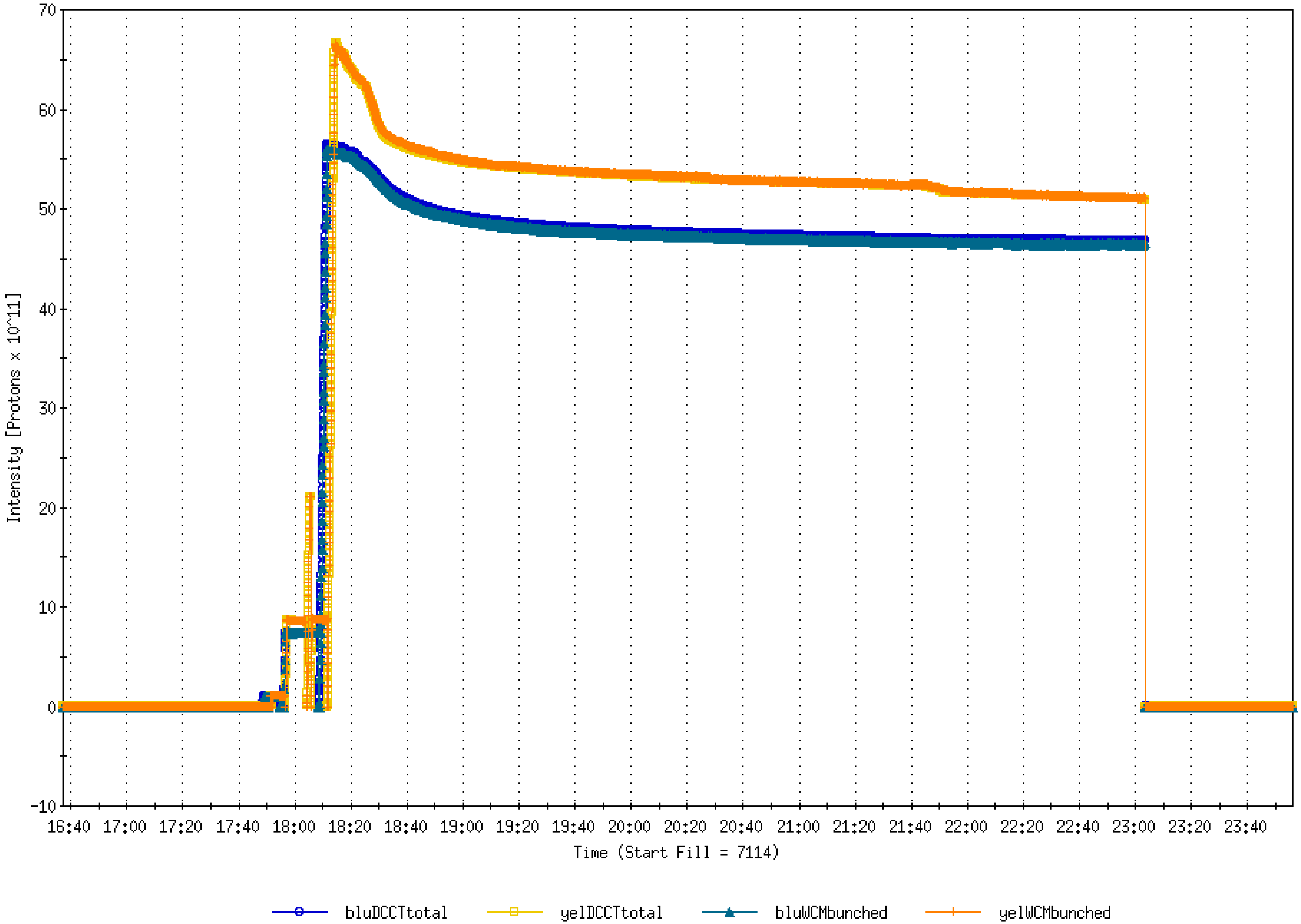


Beam Ion measurement with the WCMs

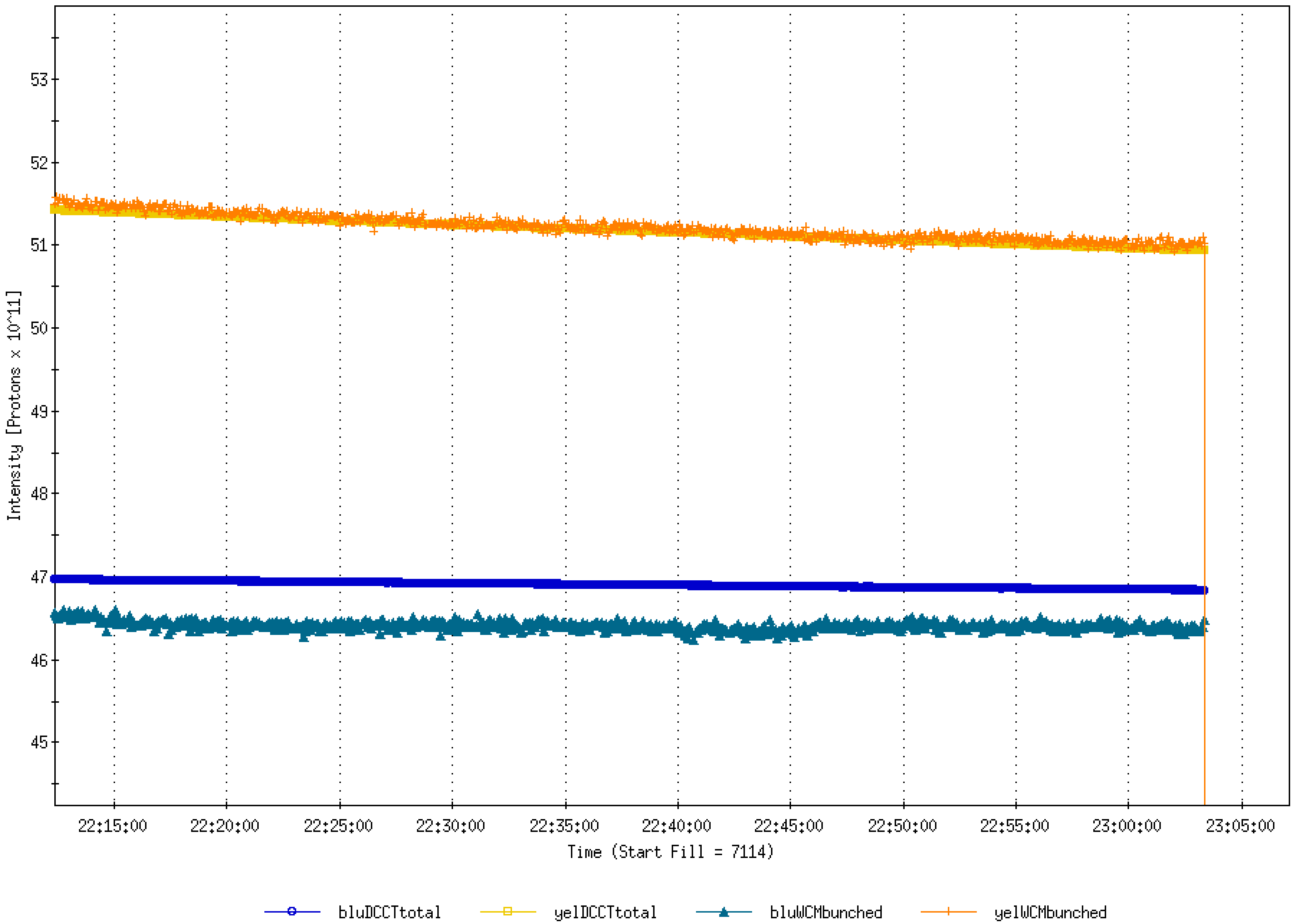


- Wall current monitor samples profile in 0.25 nsec bins
- Wide bunches seem to correspond to wide vertex
- 1st pair : 47 cm; 2nd pair : 51 cm
- Still to do : predict vertex dist. from WCM
- Alternating between bunches $\longrightarrow$ 0.125 nsec bins $\longrightarrow$ improved vertex reconstruction

Calibration of the WCMs with the DCCTs after Ramp



WCMs exhibit more noise than DCCTs



What is a Vernier Scan?

Recall $\mathcal{L}$ of identical zero-length bunch pairs with non-uniform charge distributions :

$$d\mathcal{L} = k_b \times f_{rev} \times \frac{\rho_b(x,y)dxdy \ \times \ \rho_y(x,y)dxdy}{dxdy}$$

Let $N_b = \int_{\infty}^{\infty} \int_{-\infty}^{\infty} \rho_b(x,y)dxdy$ be number of ions in blue bunch :

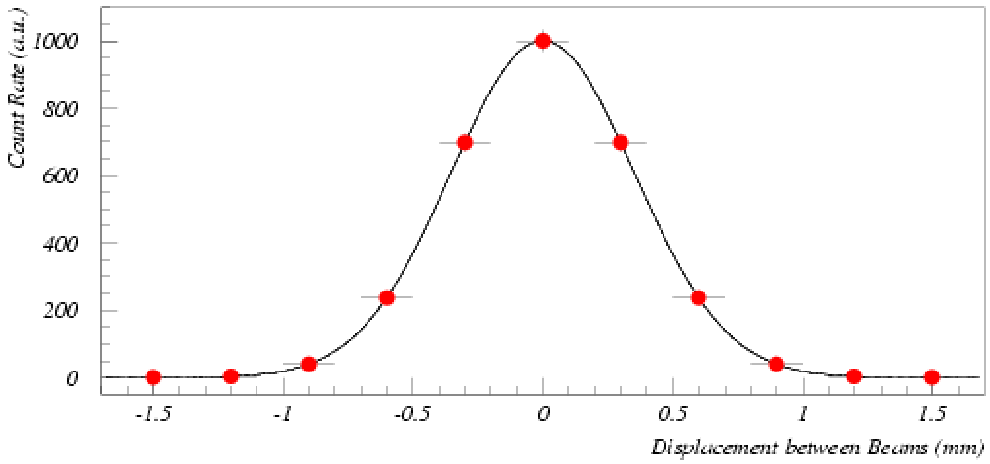
$$\mathcal{L} = k_b \times f_{rev} \times N_b \times N_y \times \frac{\int \int \rho_b(x,y) \ \times \ \rho_y(x,y)dxdy}{\int \int \rho_b(x,y)dxdy \int \int \rho_y(x,y)dxdy}$$

$$\Rightarrow k_b \times f_{rev} \times N_b \times N_y \times \frac{\int \rho_b(x) \ \times \ \rho_y(x)dx}{\int \rho_b(x)dx \int \rho_y(x)dx} \quad (\mathrm{ribbon-like\ beams})$$

- Simon van der Meer showed how to measure the overlap integral in 1968 at ISR
- Detailed knowledge of each beam's transverse profile is not required

What is a Vernier Scan?

- Consider event rate when beams displaced by h from each other :



Count Rate(h) $= \eta \int \rho_b(x)\rho_y(x-h)dx$ so area under counting rate curve :

$$\begin{aligned} Area &= \eta \times \int\int \rho_b(x)\rho_y(x-h)dzdh \\ &= \eta \times \int \rho_b(x)\left[\int \rho_y(x-h)dh\right]dx \quad \text{but} \quad \left[\int \rho_y(x-h)dh\right] = \int \rho_y(x)dx \\ &= \eta \times \int \rho_b(x)dx \int \rho_y(x)dx \end{aligned}$$

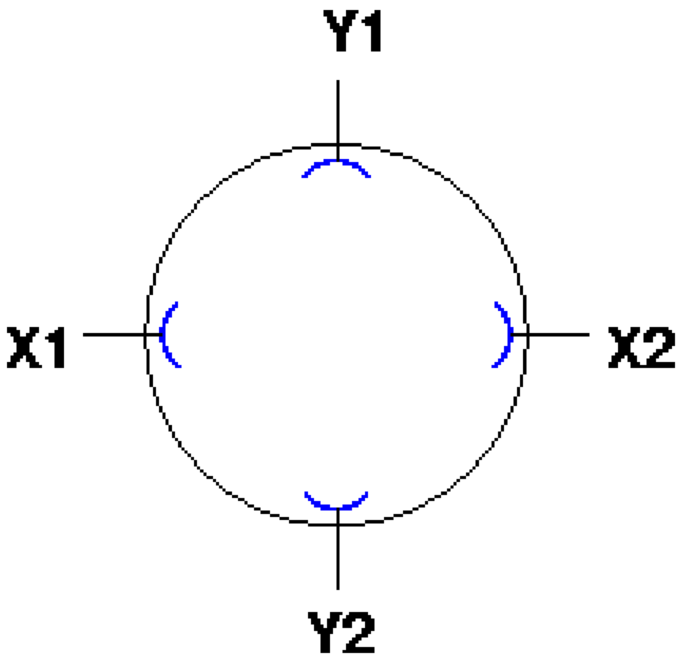
- Maximum count rate at h=0 $\Rightarrow \dot{N}_{\mathrm{max}} = \eta \times \int \rho_b(x)\rho_y(x)dx$

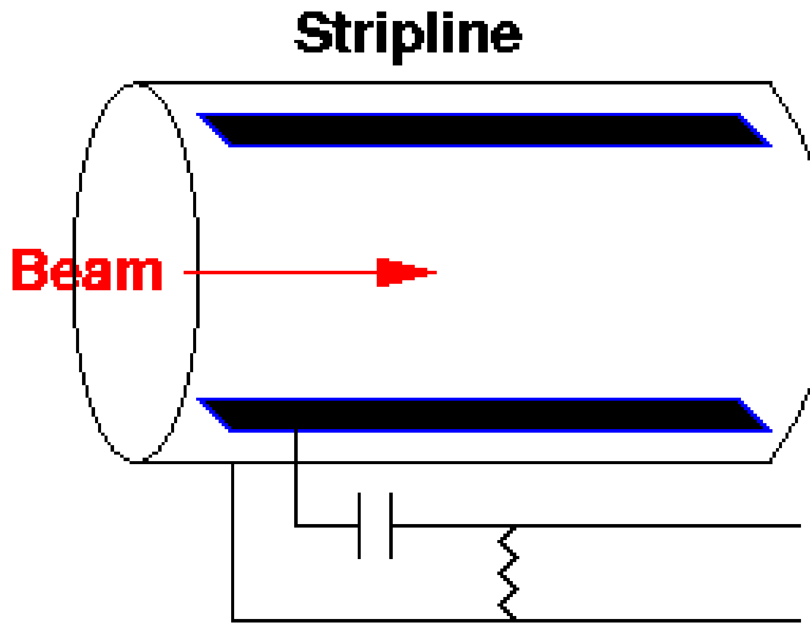
$$\Rightarrow \frac{\int \rho_b(x)\rho_y(x)dx}{\int \rho_b(x)dx \int \rho_y(x)dx} = \frac{\dot{N}_{\mathrm{max}}}{Area} \quad !!!$$

How do we do a Vernier Scan?

- Measure count rate, step beam by putting known bump in orbit, measure rate again, ...
- Rates measured with ZDC and BBC - multiple collisions not a significant problem yet
- Beam displacement known from models of beam transport through accelerator
- Displacements measured with Beam Profile Monitors (BPMs) at $\pm$ 8 meters from IP

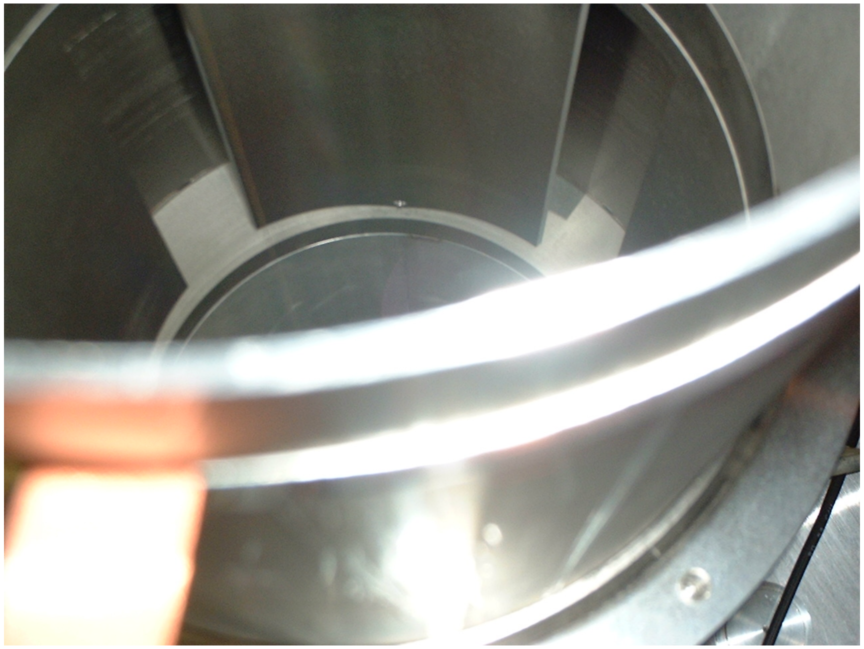
How do the BPMs work?





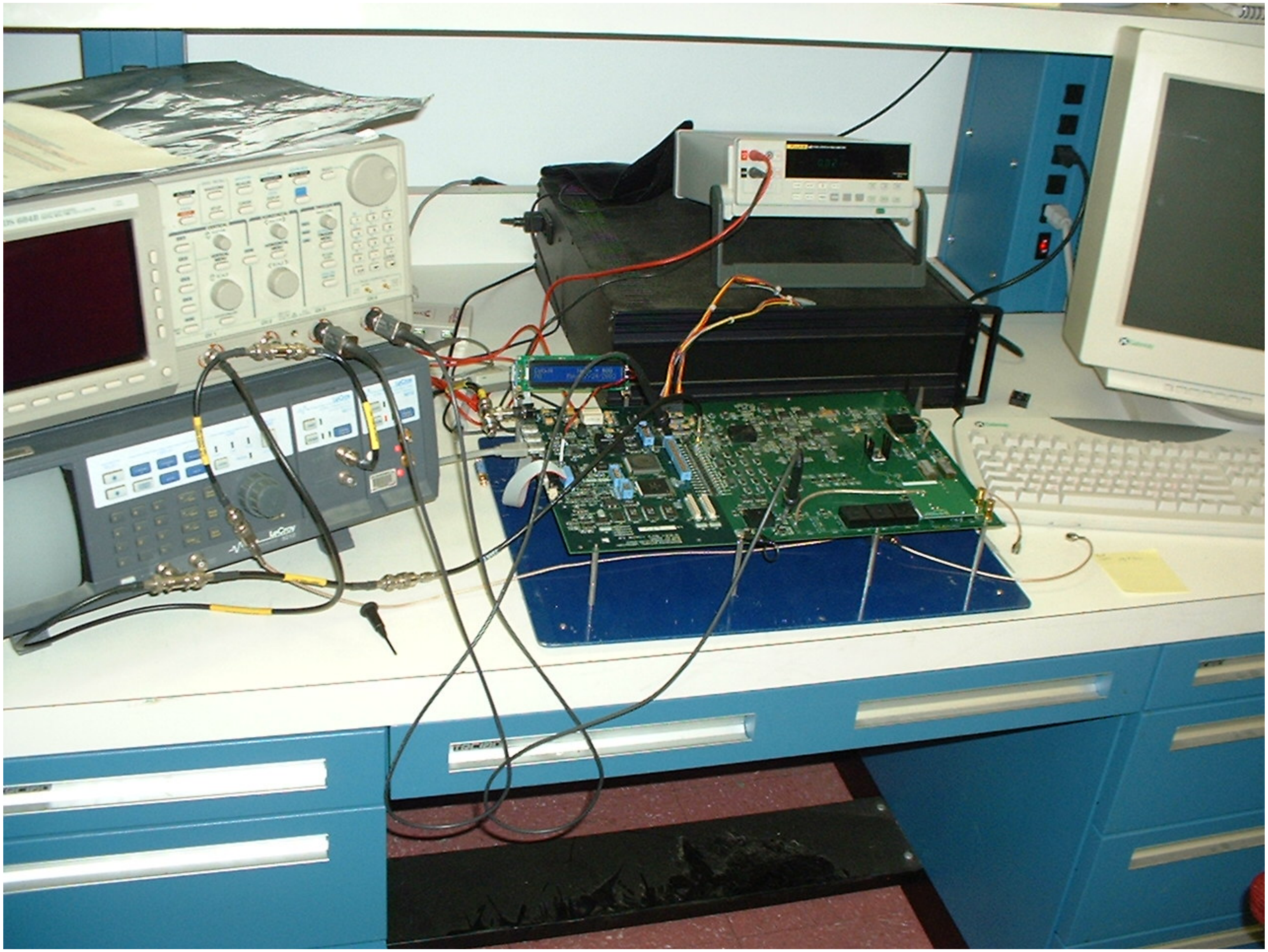
- Beam Current induces voltage(t) $\propto$ derivative of $I_b(t)$
- BPM electronics find peak of first of two double humps
- Magnitude of voltage is sensitive to total charge and position w.r.t. stripline
- X Position $\approx$ X2-X1 / X2+X1
- Many possible offsets : electrical center $\neq$ mechanical center $\neq$ orbit center ...

Some Examples of Poor Photography



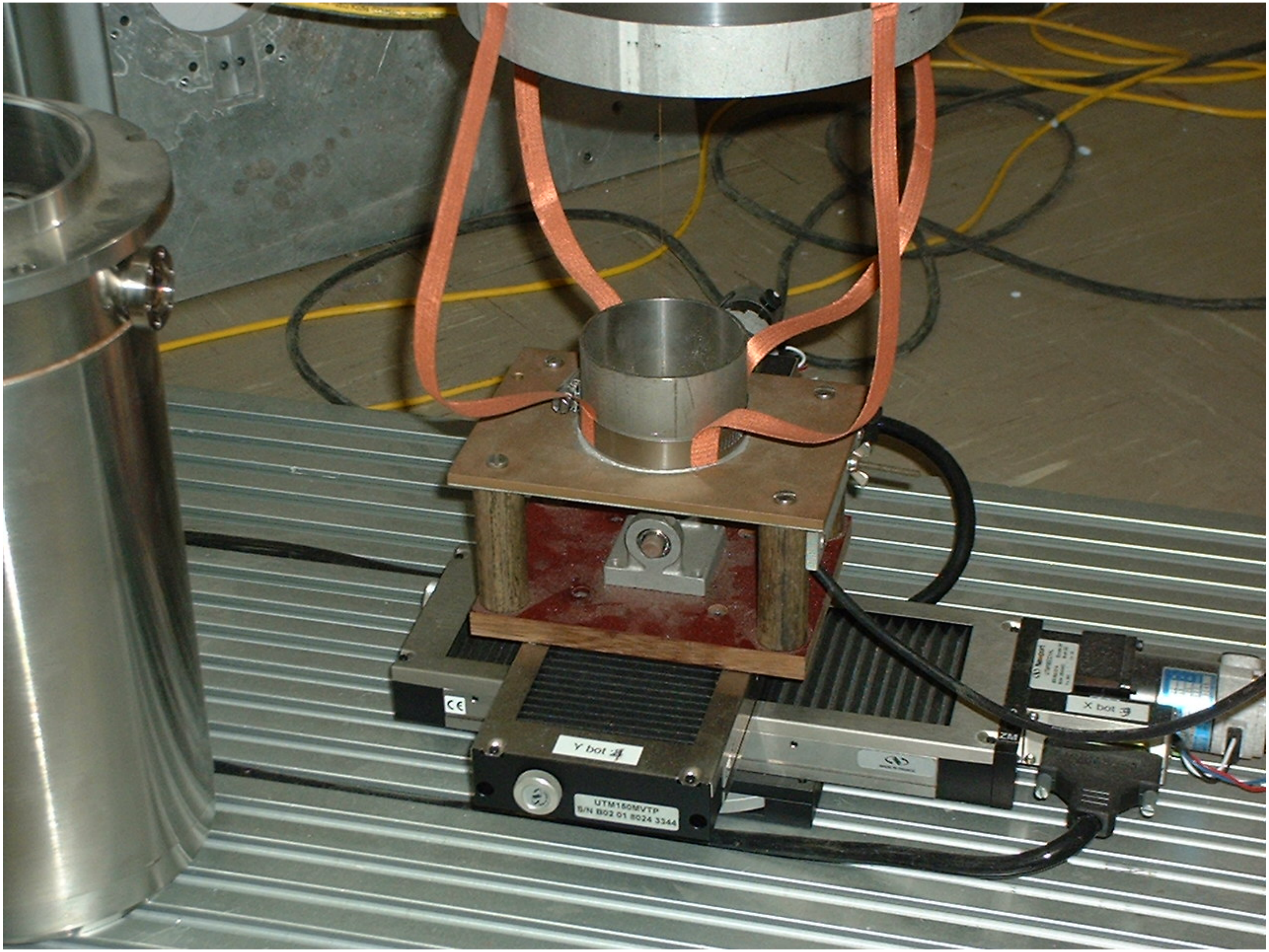
- More than 700 BPMs in RHIC and AGS
- Must make electrical connection from 4K to room temperature

Calibration of BPM electronics

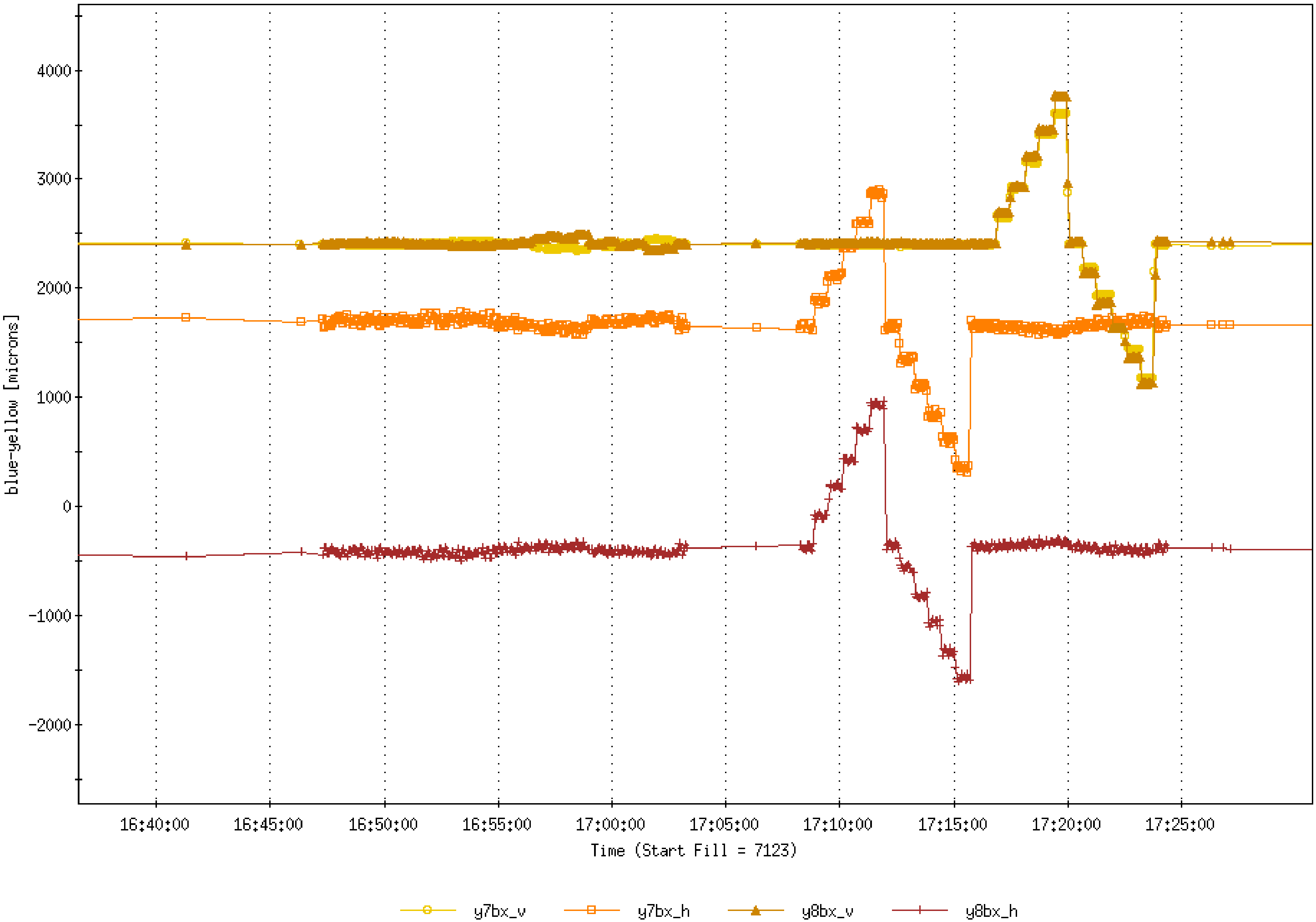


BPM wire scanning calibration apparatus

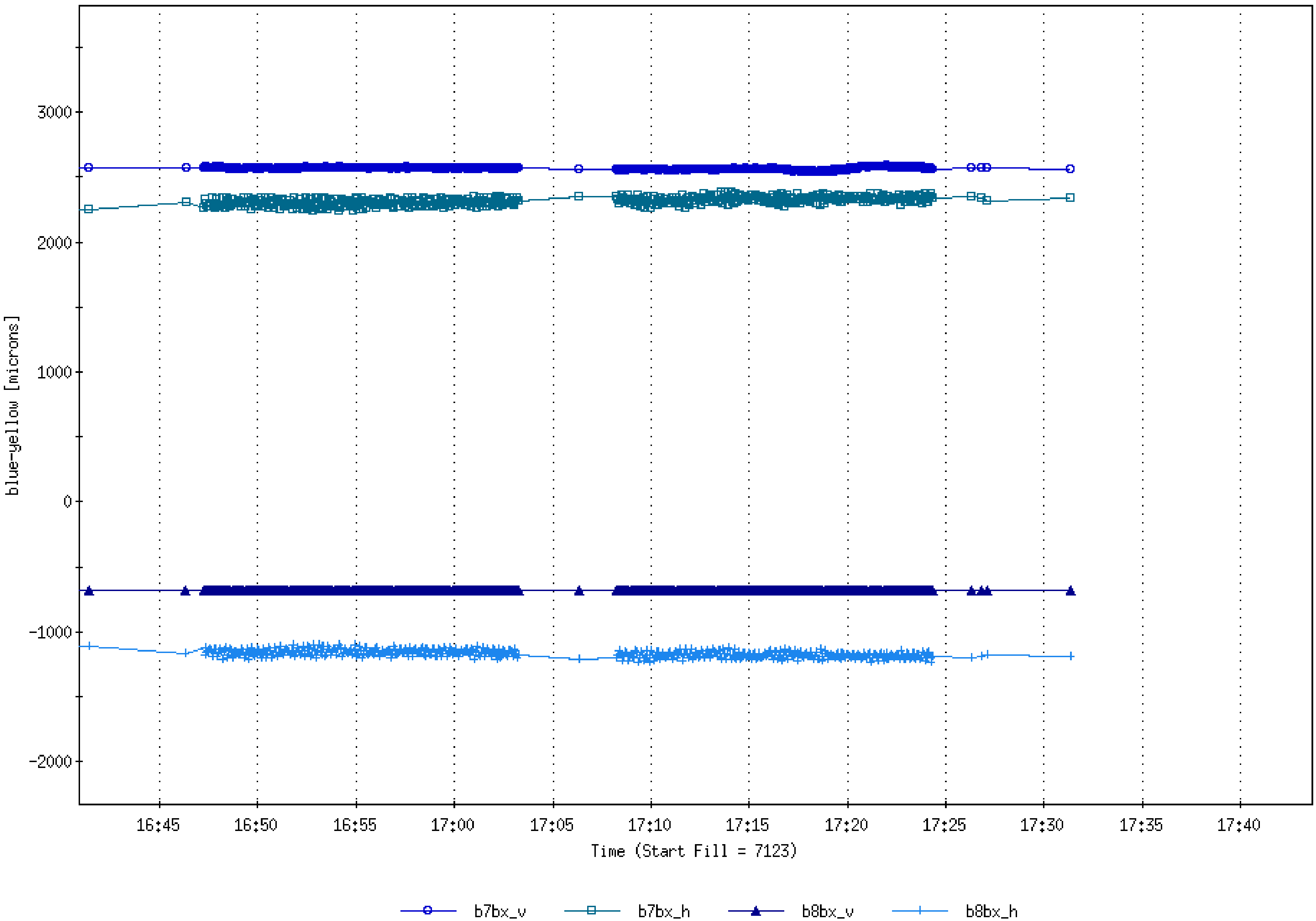
BPM wire scanning calibration apparatus closeup



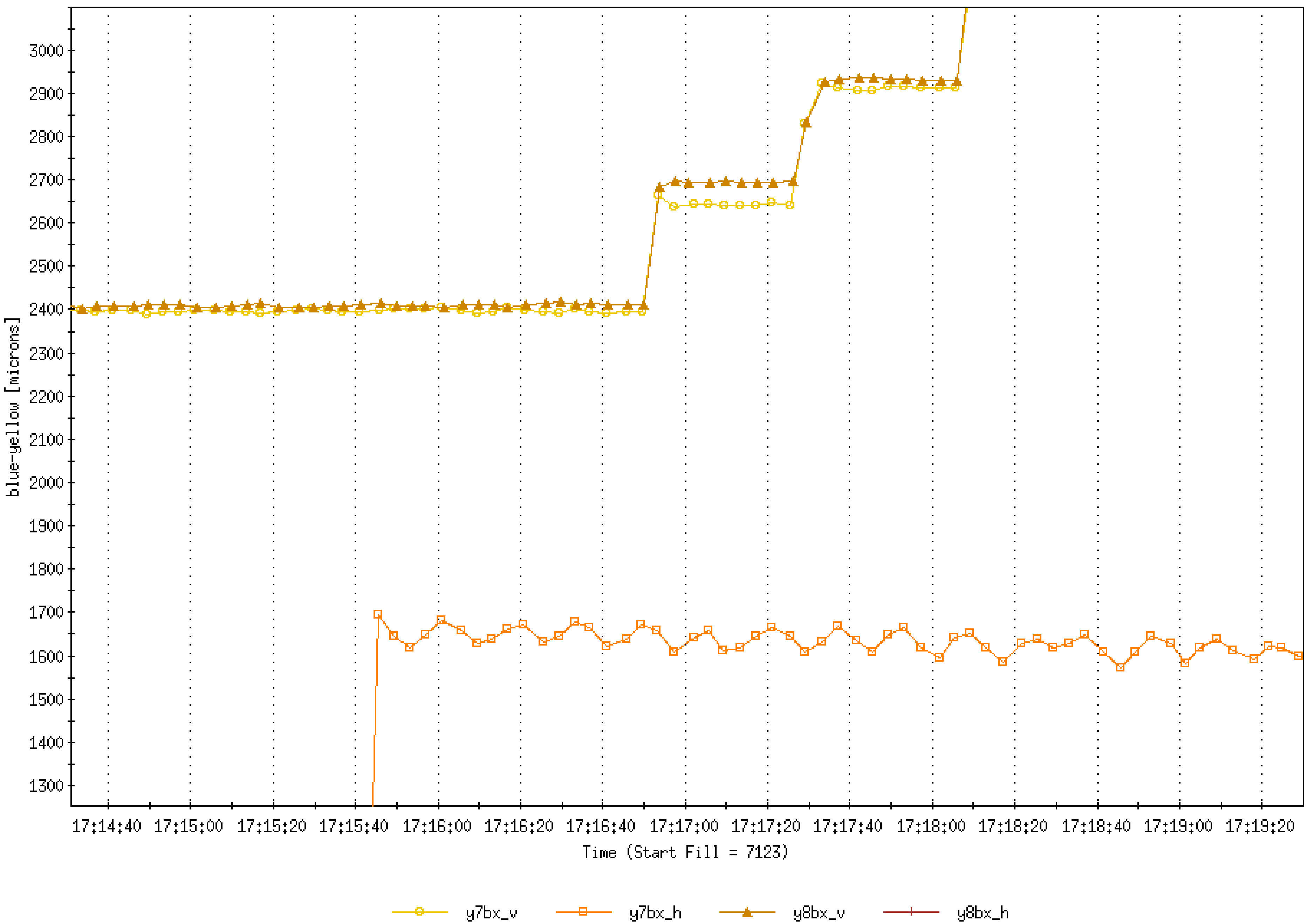
Vernier Scan 174762 showing BPMs of Yellow beam



Vernier Scan 174762 showing BPMs of Blue beam : Small coupling



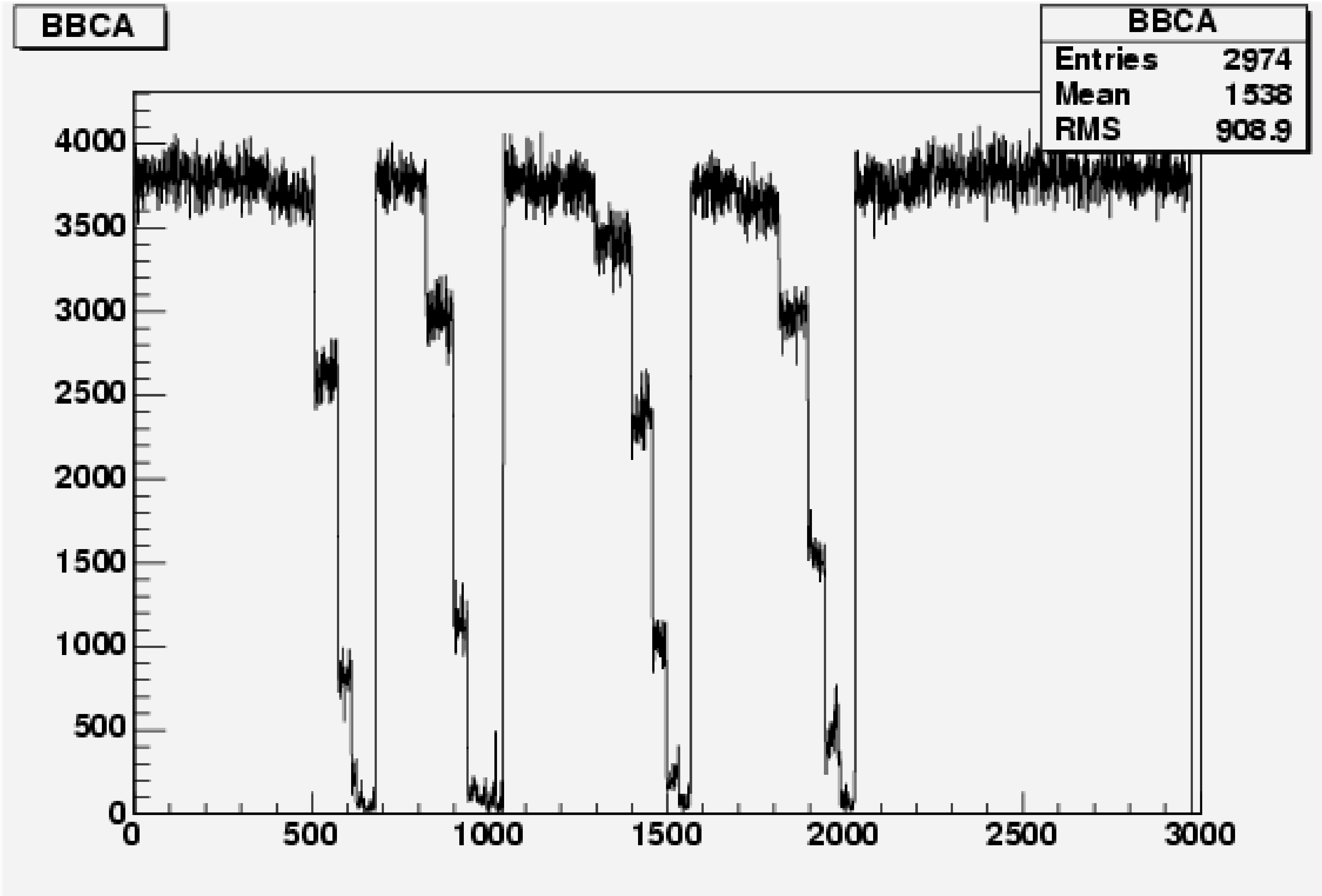
BPMs suggest beam is oscillating in horizontal



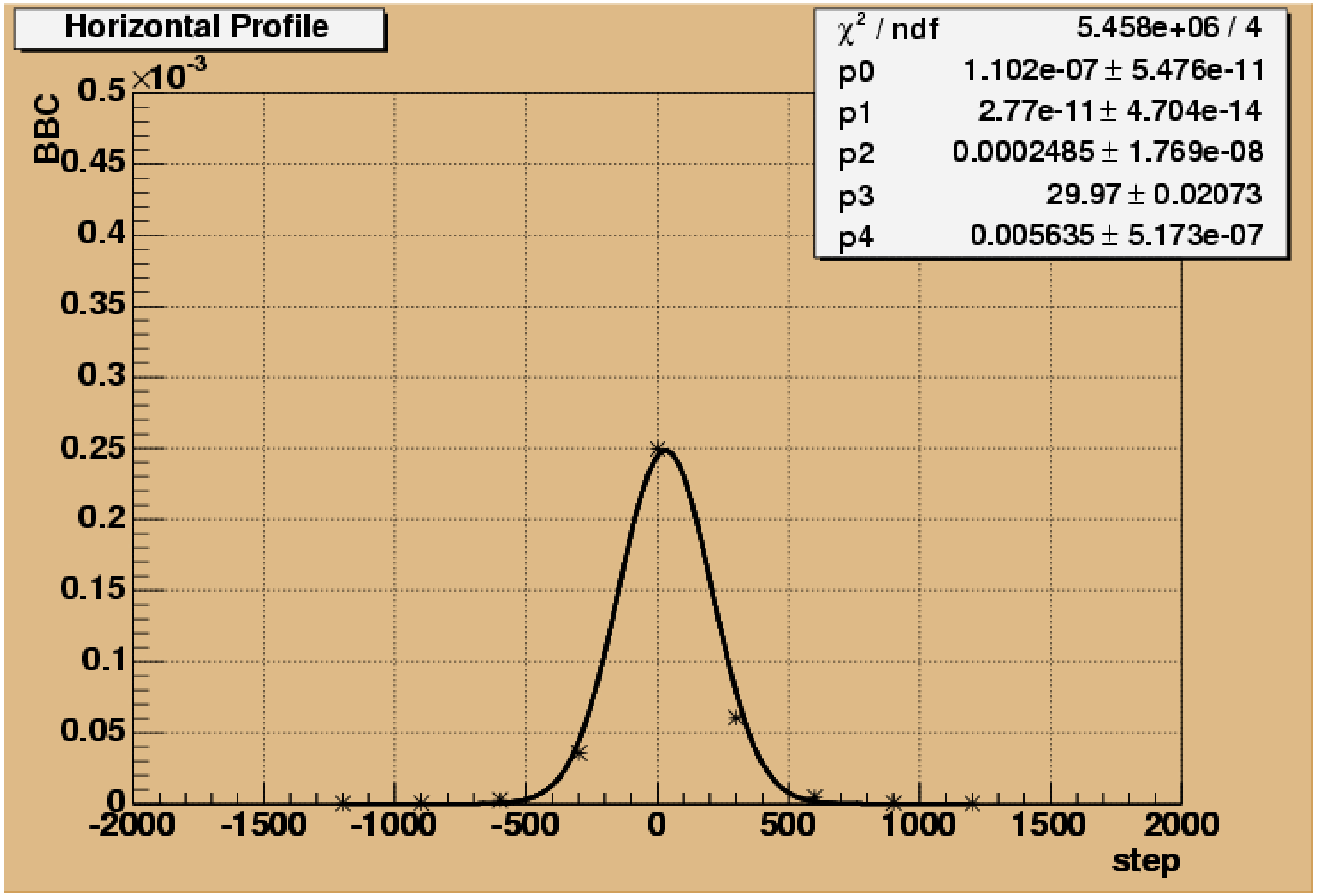
Event Rates during Vernier Scan recorded in GL1P Scalers

- Put BBCLL1, Clock, ZDCWide, ZDCNS in GL1P scalers (live counts)
- Bin and plot BBCLL1/Clock, ZDCWide/Clock, and ZDCNS/Clock
- Find steps in rates corresponding to beam motions
- Plot Event Rate versus Beam displacement
- Find plot area, peak, combine with calibrated WCM data, insert into expression for $\mathcal{L}$

Sample Data (Thanks to Robert Bennett, Oleg Eyser)



Sample Data (Thanks to Robert Bennett, Oleg Eyser)



Many Sources of Uncertainty (see AN184)

- Beams never overlap maximally - never measure $\dot{N}_{\mathrm{max}}$
- Determination of Area requires beam profile assumptions or many measurement points
- Emittance blow-up during vernier scan, coupling of beam motions
- Non-zero crossing angle, Beam position and charge uncertainties
- Multiple collision effects, afterpulsing, backgrounds
- Rotated beam axis (should measure a few stripes)
- Factors affecting calibration of BBC as $\mathcal{L}$ monitor : smearing effects, vertex position dependent efficiencies, “hourglass effect”, ...

Accounting for Crossing Angle and Hourglass Effect (see Keil)

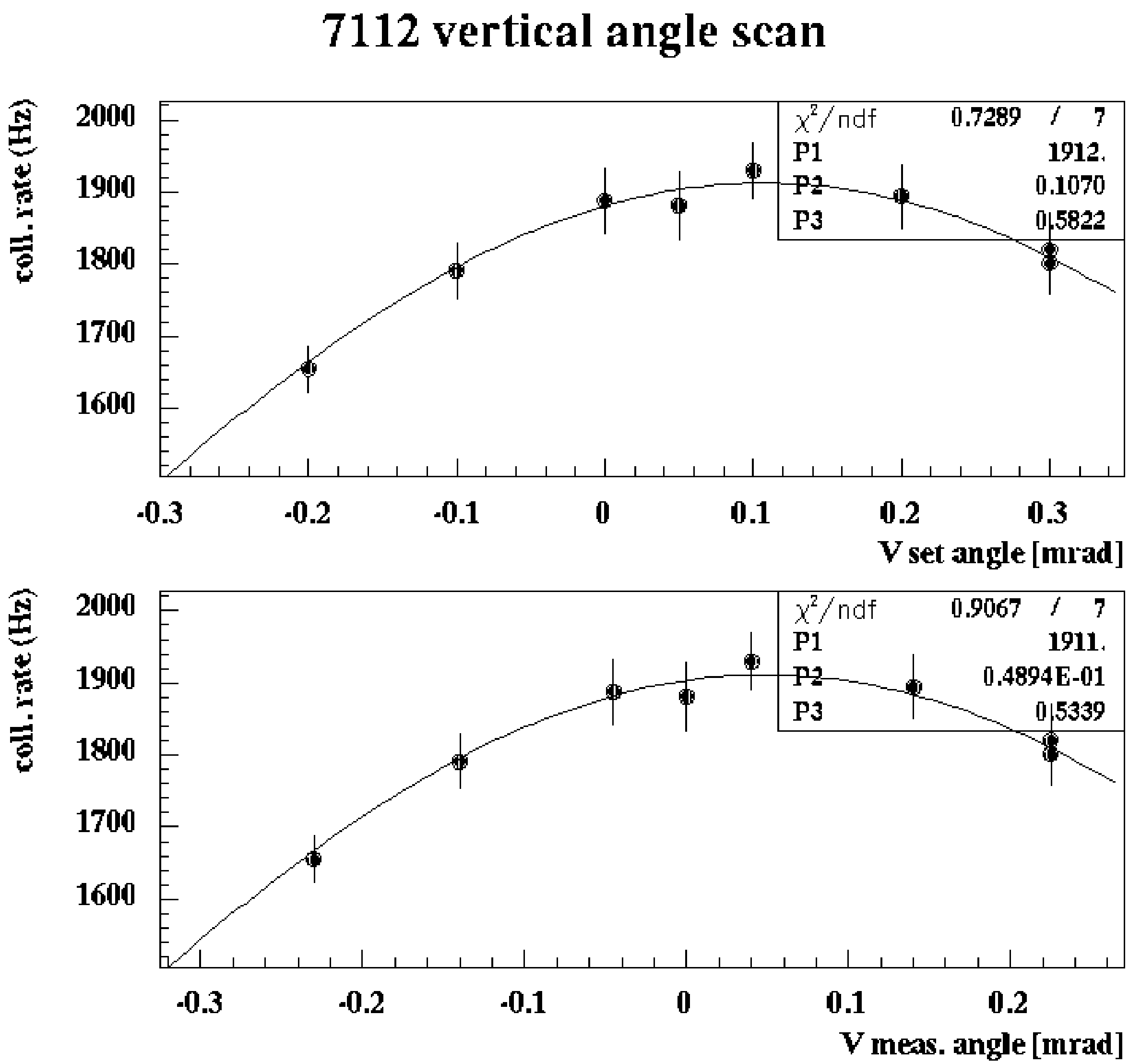
$$\mathcal{L} \propto \int \rho_b(x,y,s)\rho_y(x,y,s)\; dxdyds$$
$$\rho_b \propto \frac{N_b}{2\pi\sigma_0(1+s^2/\beta_0^2)} \exp\left(-\frac{x^2+y^2}{2\sigma_0^2(1+s^2/\beta_0^2)}\right),$$
$$\rho_y \propto \frac{N_y}{2\pi\sigma_0(1+s'^2/\beta_0^2)} \exp\left(-\frac{x'^2+y'^2}{2\sigma_0^2(1+s'^2/\beta_0^2)}\right)$$

- x', y' related to x, y by crossing angle
- Focusing account for by $\sqrt{1+s^2/\beta_0^2}$

$$\sigma_0 \approx \sqrt{\frac{\epsilon\beta_0}{6\pi\gamma}} \approx \sqrt{\frac{20\pi \times 10^{-6} \times 1}{6\pi 100}} \approx 200\ \mu m$$

- Crossing angle effect has been measured (angle scan)
- Focussing effect leads to ZDCWide beam width appearing wider than ZDCNarrow (see John Lajoie's plots)

Preliminary Results from Angle Scan (From Angelika)



Thanks for your attention